Electron Temperature Measurements in the Pegasus Toroidal Experiment

D.J. Schlossberg, G.M. Bodner, R.J. Fonck, J.A. Reusch, G.R. Winz

57th Annual Meeting of the APS Division of Plasma Physics
Savannah, Georgia
November 16-20, 2015
Electron Temperature Measurements Provide Insight Into Non-Solenoidal Startup

• Local Helicity Injection (LHI) in larger devices depends critically on confinement

• Begin quantifying confinement regimes using multi-point Thomson scattering on Pegasus ST
  – 12 radial positions, $0.15 < R_{maj} < 0.85$ m, $0.01 < T_e < 1$ keV

• $T_e (r)$ in LHI discharges found to be similar to Ohmic profiles

• Peaked density and pressure profiles inconsistent with bulk stochastic transport

• Edge-localized MHD activity suggests dual-zone confinement regime
  – Warm, Ohmic-like core; Cool, stochastic edge
PEGASUS is a Compact Ultralow-A ST

Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.15 – 1.3</td>
</tr>
<tr>
<td>R(m)</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤ .21</td>
</tr>
<tr>
<td>κ</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>τ_shot (s)</td>
<td>≤ 0.025</td>
</tr>
<tr>
<td>β_t (%)</td>
<td>≤ 25</td>
</tr>
</tbody>
</table>

Major research thrusts include:

- Non-inductive startup and sustainment
- H-mode, ELMs at low aspect ratio

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LHI Provides Non-Solenoidal Startup, Depends Critically on $T_e$

- Local Helicity Injection (LHI) uses injectors localized to the plasma edge\(^{(1)}\)

- Physics encapsulated in hierarchy of models:
  1. Maximum $I_p$ Limits\(^{(2)}\):
     \[
     I_p \leq I_{TL} \sim \left( \frac{I_{TF} I_{inj}}{w} \right)^{1/2}
     \]
     Taylor Relaxation

  2. 0-D Power Balance Model for $I_p(t)$ \(^{(3)}\):
     \[
     I_p [V_{LHI} - V_{IR} + V_{IND}] = 0; I_p \leq I_{TL}
     \]

  3. 3D Resistive MHD (NIMROD): see below

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\(^{(1)}\)more info Wed. 2pm: J.M. Perry, PO6.00001
\(^{(4)}\)J.L. Barr, GP12.00116, this session
Measurements and Simulations Suggest Edge-Localized Reconnection

- 3D Resistive MHD simulations (NIMROD) predict current rings from reconnecting LHI streams\(^{(1)}\)

- Measurements confirm maximum MHD signal localized near injector radius

- MHD analysis indicates streams localized to injector region during LHI drive\(^{(2)}\)


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• Edge localization of MHD suggests possible dual-zone confinement
  - Ohmic-like core
  - Stochastic edge

• For typical PEGASUS parameters, transport regimes separated by ~order of magnitude

• For L-mode confinement, \( I_p \) from LHI scales favorably with helicity injection rate

<table>
<thead>
<tr>
<th>Warm Core</th>
<th>Cool Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH-like confinement</td>
<td>Stochastic confinement</td>
</tr>
<tr>
<td>Low MHD</td>
<td>Large MHD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transport</th>
<th>Approx. ( \chi_e ) (( m^2/s ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical:</td>
<td>0.2</td>
</tr>
<tr>
<td>Neo-classical (trapped):</td>
<td>20</td>
</tr>
<tr>
<td>Empirical (L-mode thermal):</td>
<td>200</td>
</tr>
<tr>
<td>Stochastic:</td>
<td>2000</td>
</tr>
</tbody>
</table>

D.J. Schlossberg, 57th meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 16-20, 2015
PEGASUS Thomson Scattering Uses
Nd:YAG Laser, VPH Gratings, and ICCD

For more information, see:

D.J. Schlossberg, 57th meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 16-20, 2015
Spectrometers Employ VPH Gratings and ICCD cameras

- Custom achromatic entrance lens
- Kinematic mount provides easy interchange of gratings with different dispersions
- Image Intensified CCD (ICCD) detector
  - High quantum efficiency Gen 3 Intensifier
  - Fast gating capability to 1.2 ns

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Theoretical Performance provided courtesy of J. Ams, Kaiser Optical Systems, Inc.
Upgraded PEGASUS MPTS System Delivers Improvements in Many Areas

Wire grid polarizers significantly reduce unwanted background

New fiber bundle arrangement eases alignment

System automation increases reliability and system performance

Optimized timing improves beam quality

Collection time window optimized to capture scattered signal, reject stray light

For more details see:

G.M. Bodner
GP12.00119
this session

D.J. Schlossberg, 57th meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 16-20, 2015
Thomson Analysis Consists of Sequential Image Processing Steps

- **Single image** for each plasma shot
  - Each image contains 8 spatial channels (4 on-laser, 4 background)

- **Subtract a dark image** from plasma image to remove fixed pattern noise & offsets
  - Hot pixels
  - Camera readout amplifier offset

- **Correct for flat field** effects
  - Differing efficiencies vs. wavelength
  - Optical vignetting
Gaussian Fits Used to Obtain Electron Temperatures

- **Correct $\lambda$ mapping** for slit curvature
  - Use previous calibration with emission line lamps

- **Subtract background** channels from data channels

- **Gaussian fits** applied to obtain temperature
  - Refined analysis using Selden’s analytic formula in development

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*D.J. Schlossberg, 57th meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 16-20, 2015*
LHI Plasmas with $I_p \approx 0.14$ MA, $I_{\text{inject}} \approx 6.5$ kA
Diagnosed

- Plasmas highly reproducible

- Typically:
  - $B_T = 0.1$ T
  - $I_{\text{inj, max}} = 5.5$ kA
  - $V_{\text{inj, max}} = 900$ V
  - $t_{\text{Thomson}} = 23.225$ ms
  - $n_e(t_{\text{Thomson}}) \approx 0.7 \times 10^{19}$ m$^{-3}$

D.J. Schlossberg, 57th meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 16-20, 2015
First Measurements Show Peaked $T_e(r)$ During LHI Drive

- $T_e$ measured at 16 radial locations during helicity injection drive

- >10 data and >10 background shots averaged at each radial location
  - Greatly increases SNR

- $t_{\text{Thomson}} \sim 1.75$ ms prior to peak $I_p$
  - Bulk plasma still coupled to injectors

\[ \text{Counts} \times 10^3 \]
Peaked Density and Pressure Profiles Suggest Ohmic-like Confinement

• Scattering at each location summed over $\lambda$
  - Ersatz for electron density
  - Profile peaks near plasma $R_0$

• Pressure profile estimated as $T_e(R) \times \Sigma \text{counts}(R)$
  - Peak $p_e$~6x edge $p_e$
  - Peaked profiles inconsistent with bulk stochastic transport
  - Core heating could be from PF induction

• If scales favorably, could provide excellent target for NBI coupling

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Mapping Measured $T_\text{e}$ to Calculated Plasma Shape Provides $\langle T_\text{e} \rangle$ and $\eta_\text{e}(r)$

- Fast boundary reconstruction code estimates plasma edge\(^{(1)}\)
- Simple geometric mapping gives averaged $T_\text{e}$:
  - Volume-averaged: $\langle T_\text{e} \rangle = 85$ eV
  - Uniform $J(r)$: $\langle T_\text{e} \rangle \approx 76$ eV
    $\langle \eta_\text{e} \rangle = 1.3 \times 10^{-6}$ Ω-m
- Profiles suggest hot core, cool edge
  - Dual confinement regimes?

\(^{(1)}\)J.L. Barr, this session GP12.00116

D.J. Schlossberg, 57th meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 16-20, 2015
0-D Power Balance Model Reveals Significant Inductive Drive at $t_{Thomson}$

- Power balance model for $I_p(t)$ predicts LHI discharge performance\(^{(1)}\)

- Model represents plasma drive with **inductive**, helicity injection, and **resistive** terms
  - At $t_{Thomson}$, $V_{IND} > V_{eff}$
  - Inductive drive could provide core heating

- Understanding $V_{IR}$ term critical to model accuracy
  - Strongly dependent on $T_e$

\(^{(1)}\)J.L. Barr, *this session* GP12.00116

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L- and H-mode Electron Temperatures Investigated for \( I_p \sim 0.13 \) MA

- Thomson data collected for L- and H-mode plasmas
  - \( I_p = 130 \) kA
  - \( B_T = 0.1 \) T
  - \( \tau_{shot} \sim 20 \) ms

- \( R_{Thomson} = 35 \) cm

- Time of Thomson collection window scanned from shot-to-shot (dashed green line)
  - Early phase
  - Mid-phase
  - Late phase
L-mode Plasmas Exhibit Increasing $T_e$ Throughout Discharge

- Position of 8-channel array spanned $32.9 \text{ cm} < R_{\text{maj}} < 37.1 \text{ cm}$

- Data averaged over spatial points and multiple shots

- For initial analysis:
  - Spectral resolution $\Delta \lambda \approx 3 \text{ nm}$
  - Due to ICCD camera software, binning restricted data collection to 7 spatial locations

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H-mode Spectra Indicate Temperatures Above Spectrometer Resolution

- TS spectrometer system designed with 2 interchangeable gratings:
  1. $10 \text{ eV} < T_e < 100 \text{ eV}$
  2. $100 \text{ eV} < T_e < 1000 \text{ eV}$

- Initial studies used low-$T_e$ grating

- High-$T_e$ H-modes scatter past grating-detector wavelength limit
  - Signal close to noise floor, may distort calculated $T_e$

- Future studies will install high-$T_e$ grating for H-mode operations

For more H-mode info,
**THIS SESSION:** K.E. Thome GP12.00115, D.M. Kriete, GP12.00120
**Wed. 3pm:** M.W. Bongard PO6.00006
Future Directions

• Pursue confinement investigation of LHI discharges
  – Measure $T_e(r)$ dependence on $V_{inj}, I_{inj}$
  – Obtain $T_e(r,t)$ for typical LHI discharge
  – Use MPTS data to constrain LHI equilibrium reconstruction
  – Identify role of $T_e(r)$ in optimizing a discharge for handoff to $P_{aux}$

• Measure ultra-low aspect ratio H-mode plasmas
  – Pedestal characteristics
  – Core temperatures
  – $T_e$ just prior and just after LH transition
Multipoint Thomson Scattering Now Producing Initial Physics Results

- First measurements of $T_e(r)$ during Local Helicity Injection discharges
  - Peaked profiles inconsistent with bulk stochastic transport
  - Localized MHD suggestive of dual-zone confinement
  - If Ohmic-like confinement scales with $V_{inj}$, LHI plasmas provide excellent target for direct NBI coupling

- 0D power balance model for $I_p(t)$ shows significant inductive drive during Thomson collection time
  - Could provide source of core heating
  - Fast boundary reconstruction provides $<T_e>$ and $\eta(r)$

- L- and H-mode plasmas display increasing $T_e$ throughout discharge
  - L-mode $T_{e,max} \sim 150$ eV
  - H-mode $T_e > 200$ eV (will confirm with upgraded system)
Electron Temperature Measurements Provide Insight into Non-Solenoidal Startup

**PEGASUS is a Compact Ultra-Low A ST**

LHI Provides Non-Solenoidal Startup, Depends Critically on $T_e$

Measurements and Simulations Suggest Edge-Localized Reconnection

Experiments on **PEGASUS May Determine Dominant LHI Confinement Modes**

**PEGASUS Thomson Scattering Uses Nd:YAG Laser, VPH Gratings, and ICCD**

Spectrometers Employ VPH Gratings and ICCD Cameras

LHI Plasmas with $I_p \sim 0.14$ MA, $I_{\text{inj}} \sim 6.5$ kA Diagnosed

Upgraded **PEGASUS MPTS System Delivers Improvements in Many Areas**

**Thomson Analysis Consists of Sequential Image Processing Steps**

Gaussian Fits Used to Obtain Electron Temperatures

Peaked Density and Pressure Profiles Suggest Ohmic-Like Confinement

LHI Plasmas with $T_e$ Diagnostic for $I_p \sim 0.13$ MA

**First Measurements Show Peaked $T_e(r)$ During LHI Drive**

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L-mode Plasmas Exhibit Increasing $T_e$ Throughout Discharge

H-mode Spectra Indicate Temperatures Above Spectrometer Resolution

D-D Power Balance Model Reveals Significant Inductive Drive at $\eta_{\text{Thomson}}$

Reprints